

# ELECTRICAL AND ELECTRONIC MATERIALS

**Code: EEC/EPM1160**

**Lecture: 3**

**Tutorial: 1**

**Total: 4**

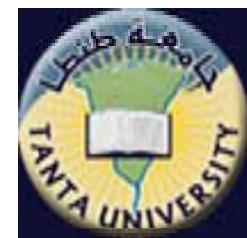
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# Mechanisms of Polarization

It is important to define the dielectric constant  $\epsilon_r$  and dielectric susceptibility  $\chi$  of a material as functions of basic variables of the materials, e.g. the angular frequency and temperature

$$\chi = \chi (\omega)$$

$$\chi = \chi (T)$$

# Mechanisms of Polarization

There are four kinds of polarization mechanisms

- 1      Interface polarization
- 2      Electronic polarization "atom or atomic polarization"
- 3      Ionic polarization
- 4      Orientation polarization

# Mechanisms of Polarization

A combination of these polarization mechanisms may act simultaneously.

Atomic polarization is always present in any material and thus occurs together with other mechanisms in the material

Real materials thus can be very complicated in their dielectric behaviour

# Mechanisms of Polarization

## Interface polarization

Surfaces, particle boundaries, inter-phase boundaries may be charged and contain dipoles

Interface polarization occurs when there is an accumulation of charges at an interface between two materials or between two regions within a material

These dipoles may be oriented under an external field and thus contribute to the polarization of the material

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# Mechanisms of Polarization

## Interface polarization

Interface polarization is normally omitted from the discussion since it has special characteristics that completely differ from the other three mechanisms

There are no straightforward methods to calculate the charges on interfaces and the nature of their contribution to the total polarization of a material is very complex

Only the last three mechanisms will be discussed

# Electronic Polarization

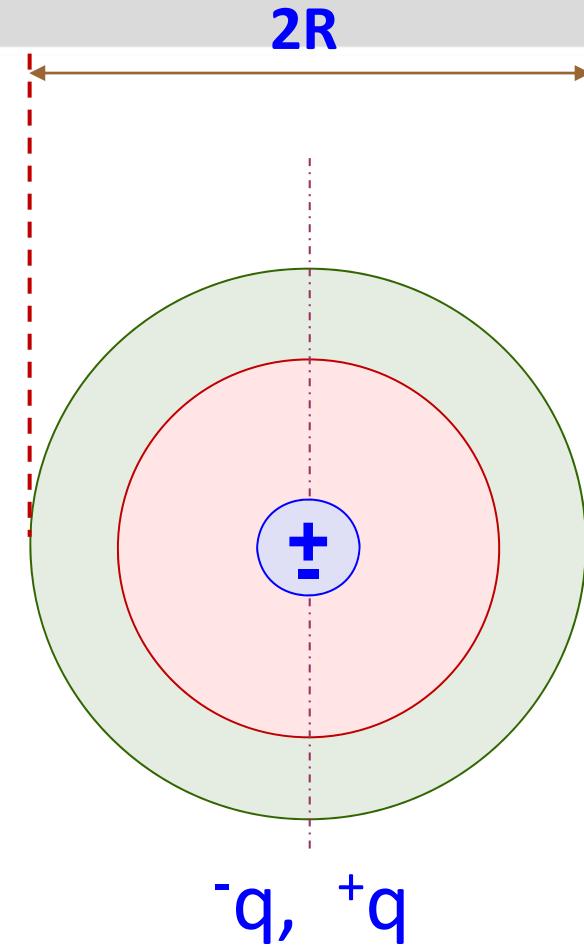
A point charge  $+q$  in the nucleus

An equal and opposite charge  $-q$   
homogeneously distributed in the  
volume of the atom

The volume of the atom is given  
as:

$$V = \frac{4}{3} \pi R^3$$

With  $R$  is the radius of the atom



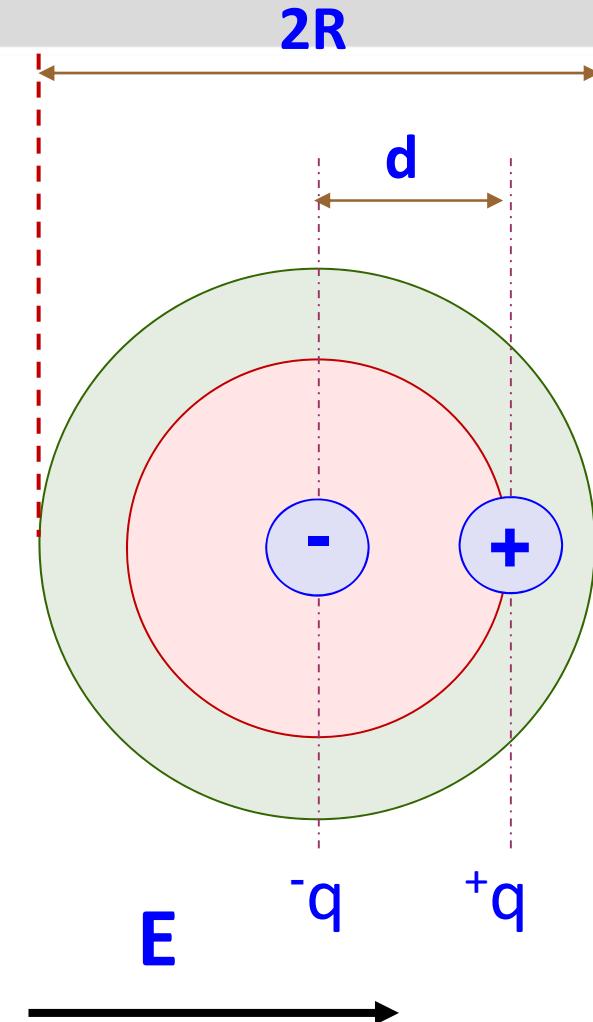
# Electronic Polarization

The charge density  $\rho$  of the electrons is given as:

$$\rho = -\frac{3q}{4\pi R^3}$$

With an electrical field  $E$ , a force  $F_1$  is produced to act on the charges

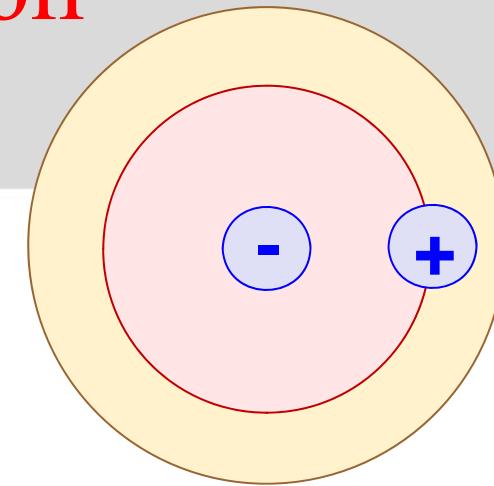
$$F_1 = q E$$



# Electronic Polarization

The positive charge in the nucleus and the equivalent negative charge of the electron cloud will experience forces in different directions and will become shifted

The attractive force between the centres of charges will balance the separating force of the external field and hence the atom will reach an equilibrium situation with a definite separation distance **d**.

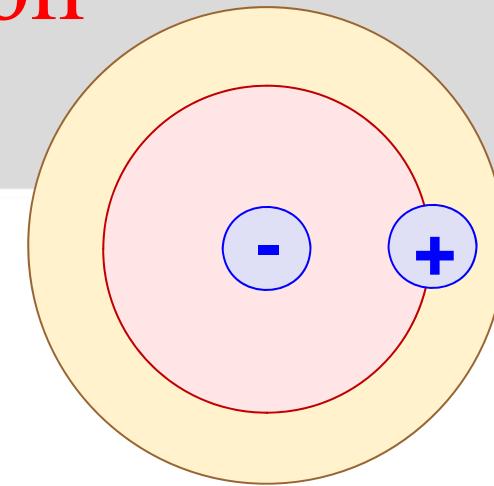


$$q_d = \frac{q d^3}{R^3}$$

# Electronic Polarization

**There are two values of charges**

- The total charge "q" inside the sphere
- The fraction of the charge of the electrons contained in the sphere with radius "d"



The attractive force  $F_a$  thus is given by:

$$F_a = \frac{q q_d}{4\pi\epsilon_0 d^2}$$

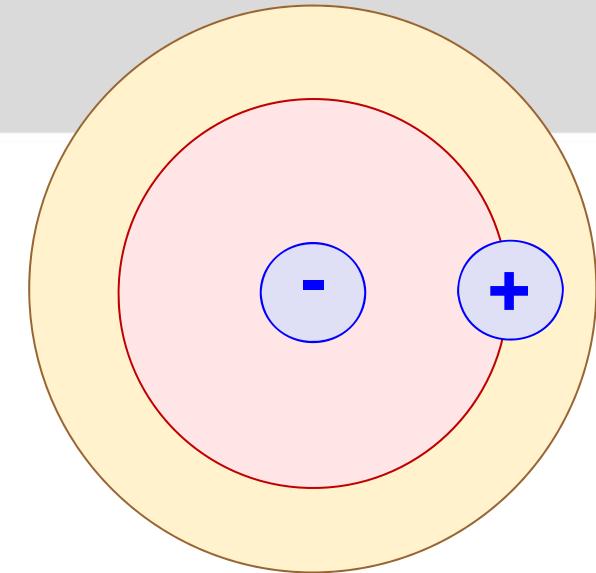
$$q_d = \frac{q d^3}{R^3}$$

where  $q_d$  is the fraction of the charge of the electrons contained in the sphere with radius “d”

# Electronic Polarization

The attractive force between the charges is given as:

$$F_a = \frac{q^2}{4\pi\epsilon_0 R^3} d$$



The equilibrium takes place when  $F_1$  is equal to  $F_a$

The distance  $d$  is called the equilibrium distance  $d_E$

$$q \cdot E = \frac{q^2}{4\pi\epsilon_0 R^3} d_E$$

# Electronic Polarization

$$q \cdot E = \frac{q^2}{4\pi\epsilon_0 R^3} d_E$$



$$d_E = \frac{4\pi\epsilon_0}{q} R^3 E$$

$$\mu = q d_E = 4 \pi \epsilon_0 R^3 E$$

$$P = 4 \pi \epsilon_0 N R^3 E$$

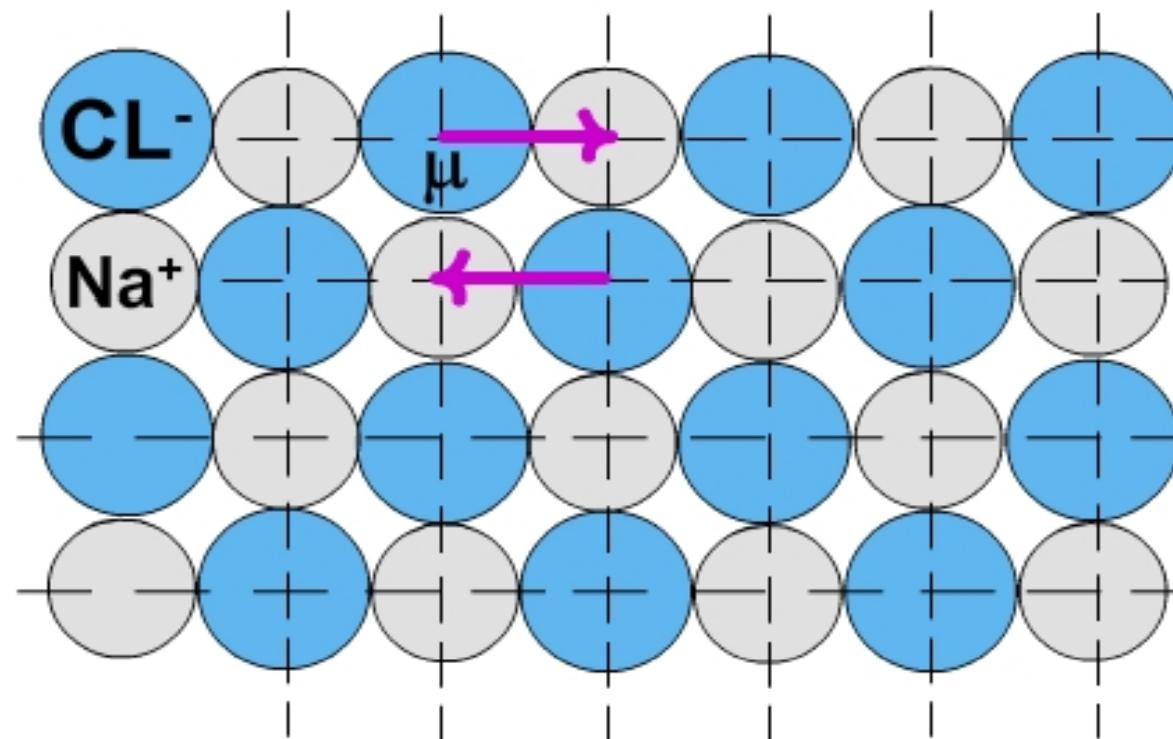
Where: N is the density of dipoles per m<sup>3</sup>

$$\chi_{atom} = p / \epsilon_0 E = 4 \pi N R^3$$

# Ionic Polarization

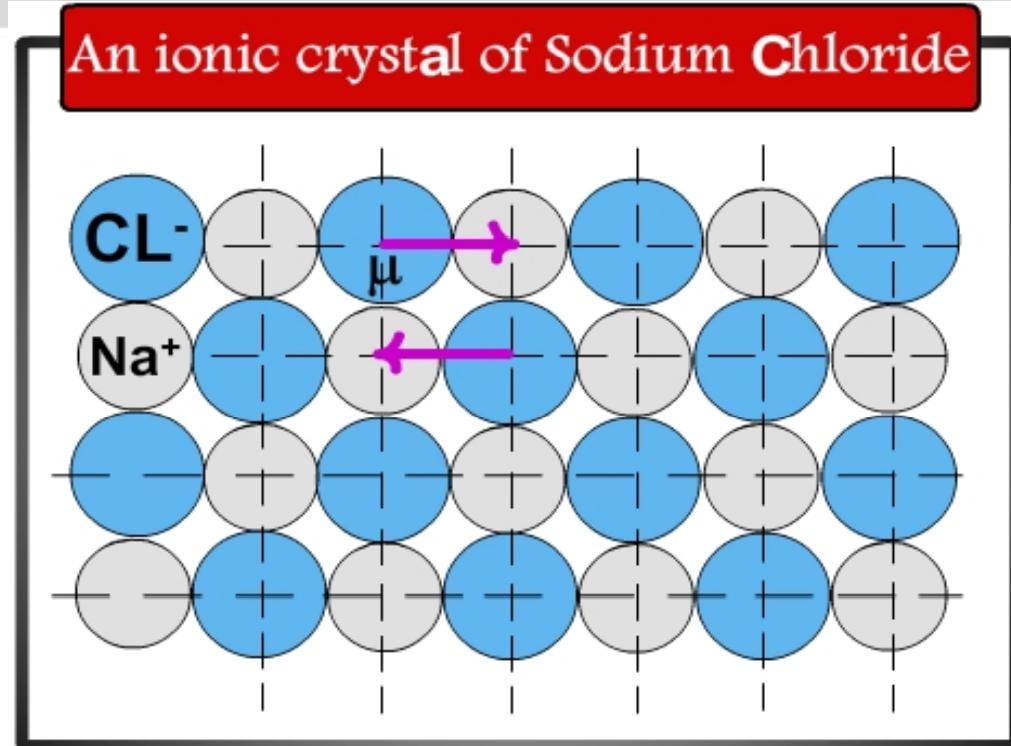
For the ionic crystal of Sodium Chloride NaCl, the lattice consists of Sodium ( $\text{Na}^+$ ) and Chlorine ( $\text{Cl}^-$ ) dipoles

An ionic crystal of Sodium Chloride



# Ionic Polarization

Each  $\text{Na}^+ - \text{Cl}^-$  pair is a natural dipole and the polarization of a given volume is zero since for every dipole moment there is an adjacent dipole moment with equal magnitude and opposite sign



**The dipoles cannot rotate and their direction is fixed**

# Ionic Polarization

After applying an electrical field, the ions are subjected to forces in opposite directions

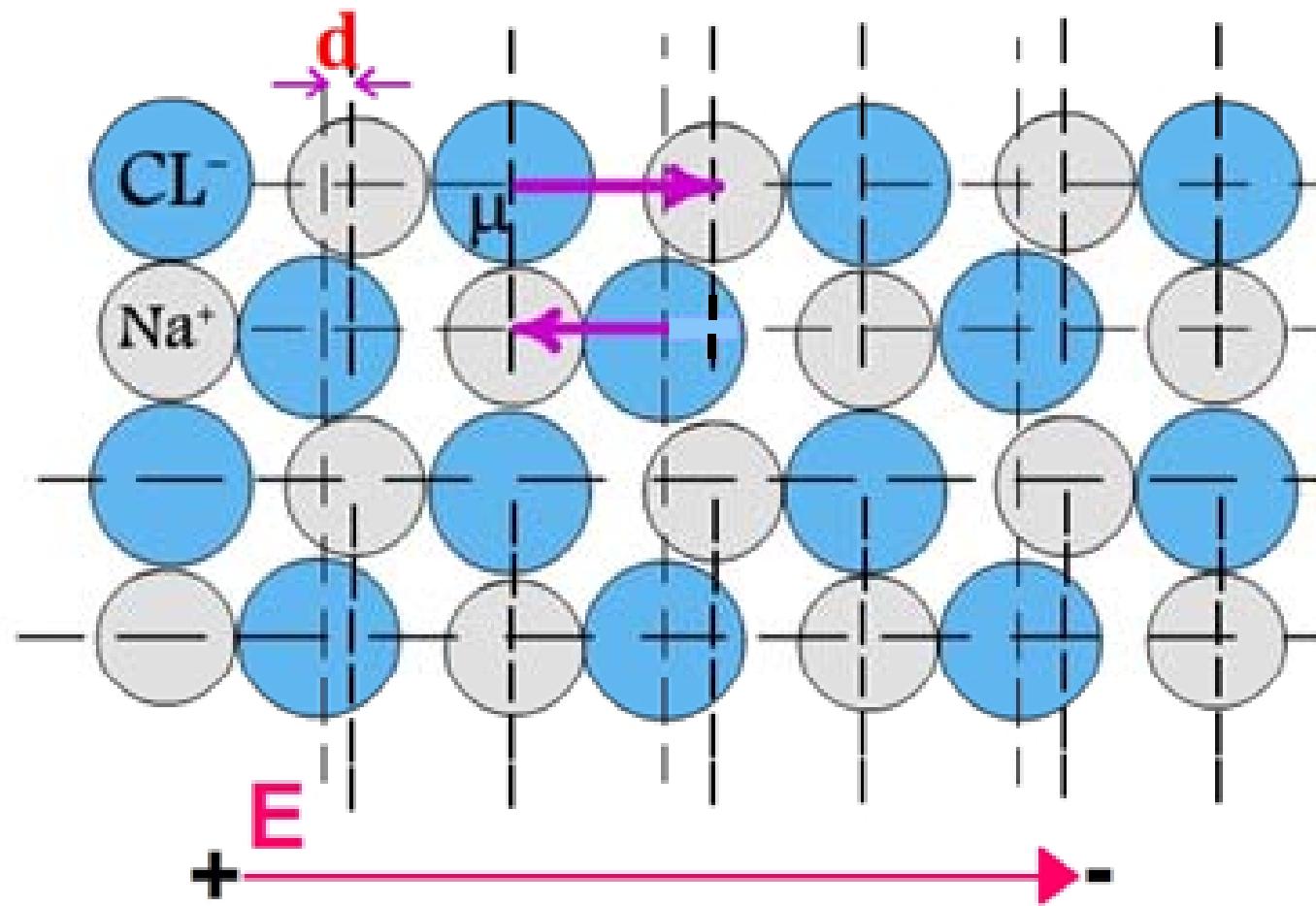
The lattice distorts a little bit, where  $\text{Na}^+$  ions move in a certain direction and  $\text{Cl}^-$  ions move in the other direction

The dipole moments between adjacent Na-Cl pairs in field direction have **different values**

There is a net dipole moment in a finite volume

# Ionic Polarization

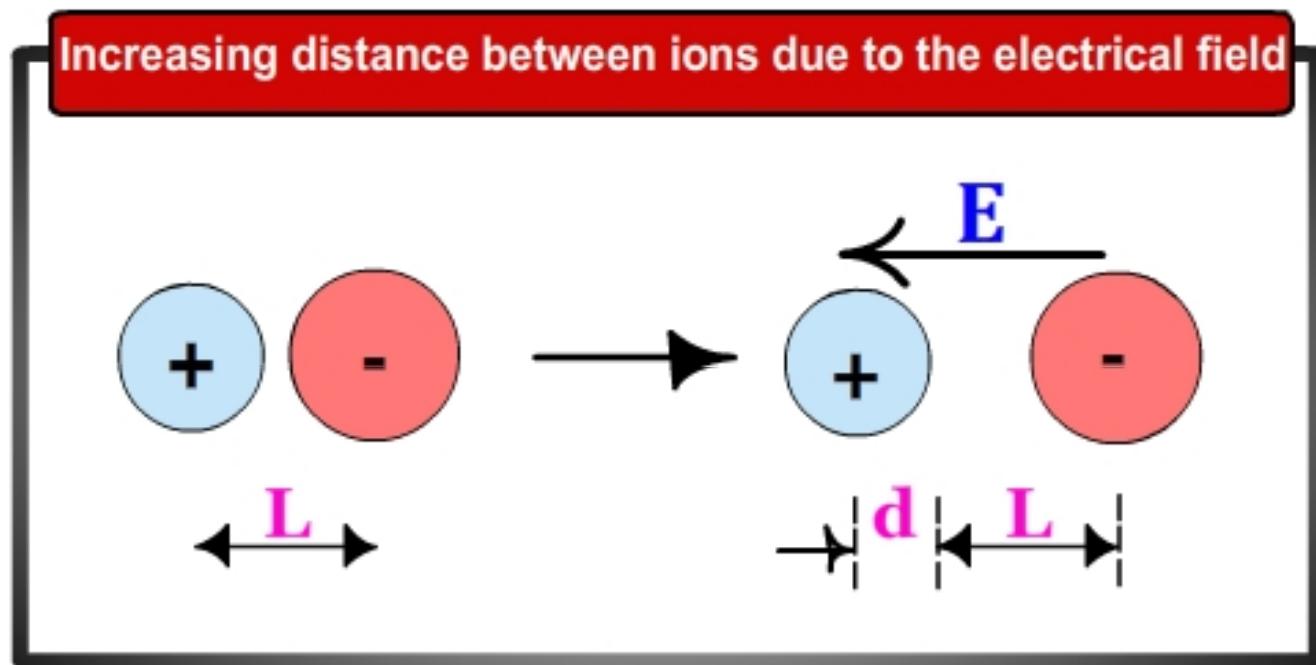
Electrical field applied to an ionic crystal of Sodium Chloride



# Ionic Polarization

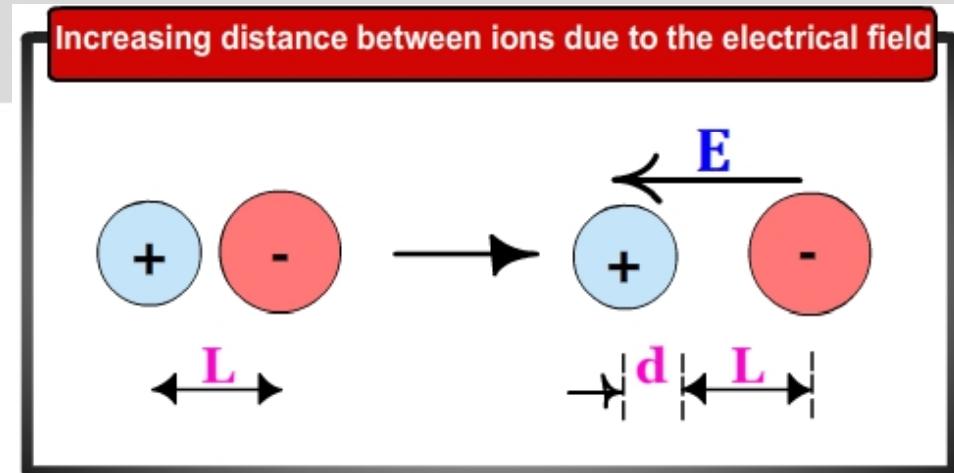
Considering only one dipole in the field direction, where the distance between the ions is increased by a distance "d", the force  $F_1$  causing the distance increase can be given by equation

$$F_1 = q E$$



# Ionic Polarization

A restoring force  $F_b$  results from the binding action when the distance between the ions increases



A linear relation can be used between binding force and deviation from the equilibrium distance

$$F_b = K_s \cdot d$$

$k_s$  is the "spring constant" of the bond

$$K_s = Y \cdot d_0$$

# Ionic Polarization

For equilibrium status,  $F_1 = F_b$

$$F_1 = q E, \quad F_b = Y \cdot d_0 \cdot d$$

$$d_{E\text{-io}} = \frac{q E}{Y \cdot d_0}$$

$$\mu = \frac{q^2 E}{Y \cdot d_0}$$

$$P = \frac{N q^2 E}{Y \cdot d_0}$$

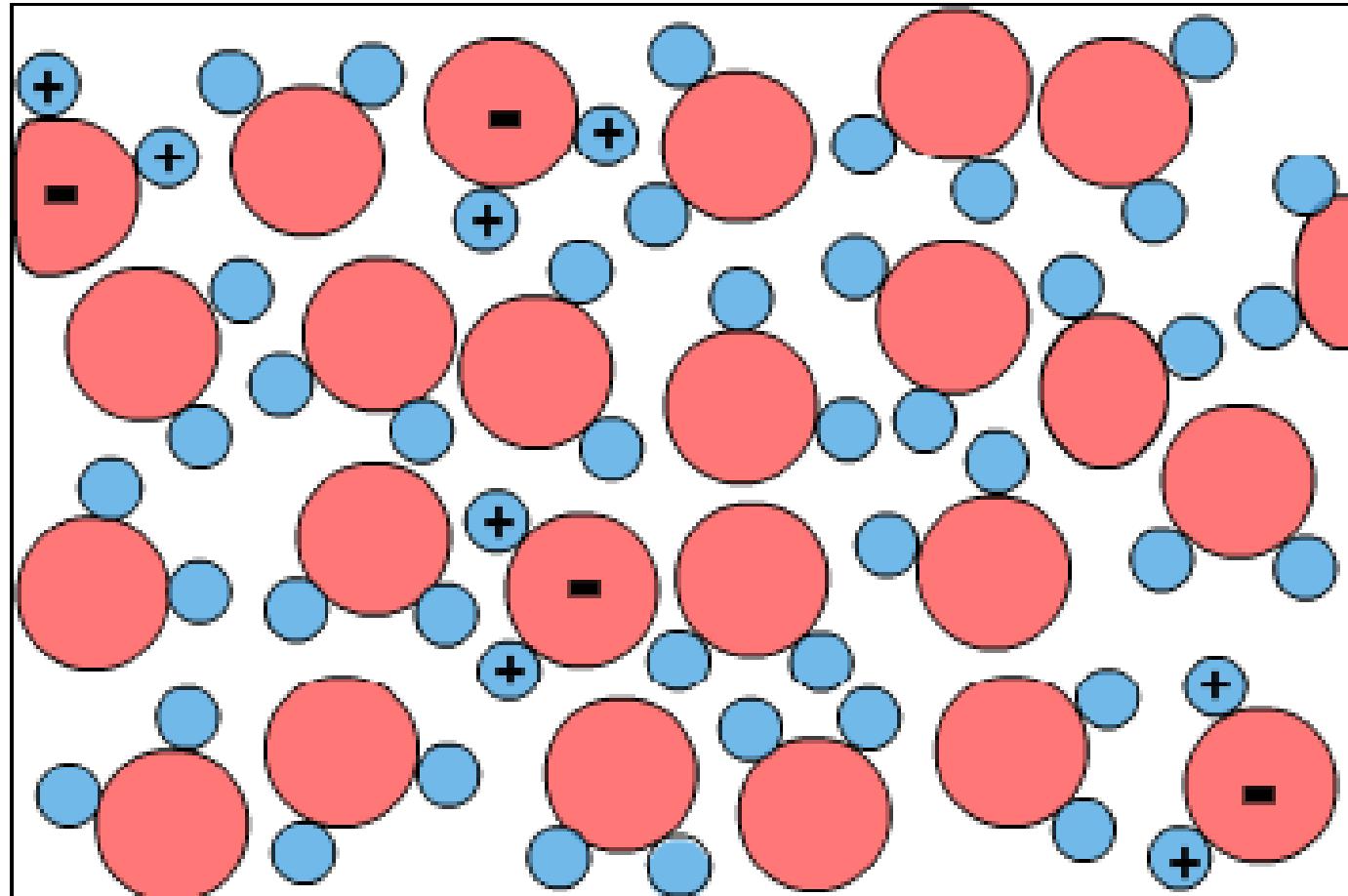
$$\chi_{\text{ion}} = \frac{N q^2}{Y \varepsilon_0 d_0}$$

# Orientation Polarization

- Unlike the ionic polarization, orientation polarization requires that the materials under consideration have independent permanent dipoles that **can rotate freely**
- This is commonly found in **liquid water**, where each water molecule represents an independent dipole that has a specific orientation regardless of the other molecules
- With the movement of the molecules, this orientation changes continuously

# Orientation Polarization

Natural dipole moments in water molecules



# Orientation Polarization

With time, the structure may look totally different in detail, but still has the same characteristics

This configuration forms natural dipoles since the negatively charged  $O_2$  atoms and the two positively charged  $H_2$  atoms have different centres of charge

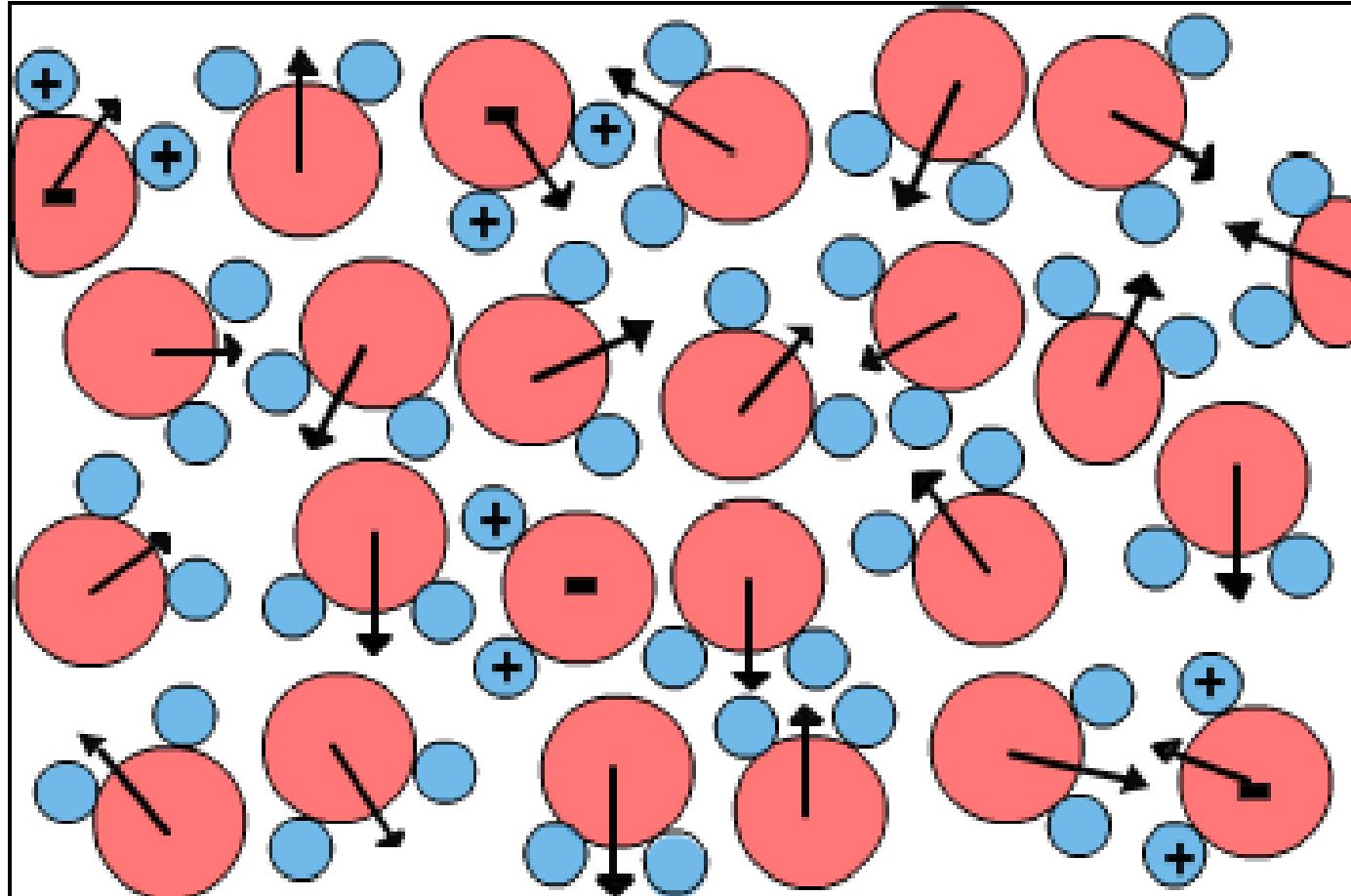
The molecules carry dipole moments that are equal in magnitude but have different directions

The total dipole moment at any instant is the vector sum of the individual dipole moments

For randomly oriented dipoles, the sum of all dipole moments will be zero

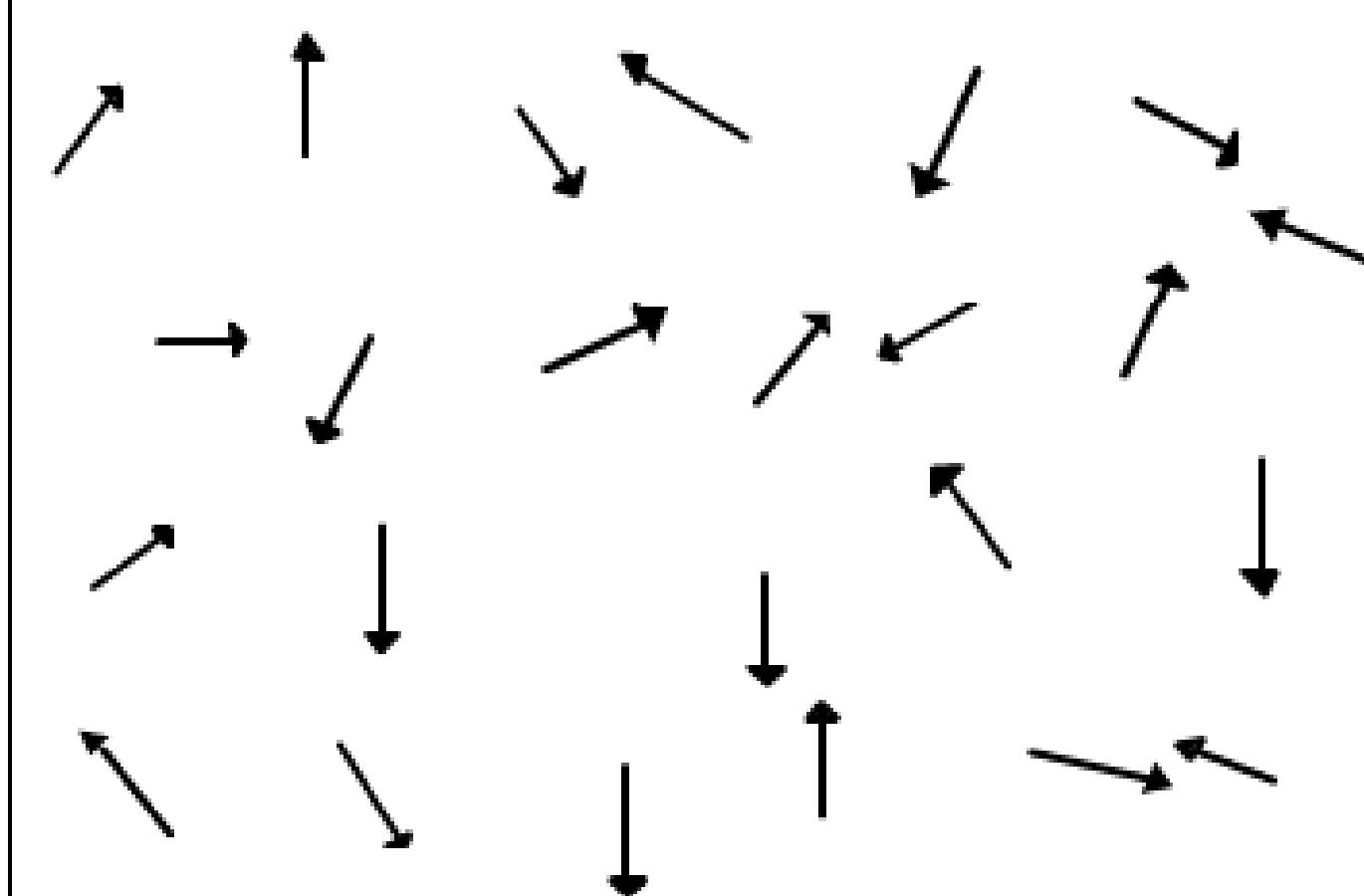
# Orientation Polarization

Natural dipole moments in water molecules



# Orientation Polarization

Natural dipole moments in water molecules



# Orientation Polarization

If an electrical field  $E$  is introduced, the dipoles will rotate into the field direction

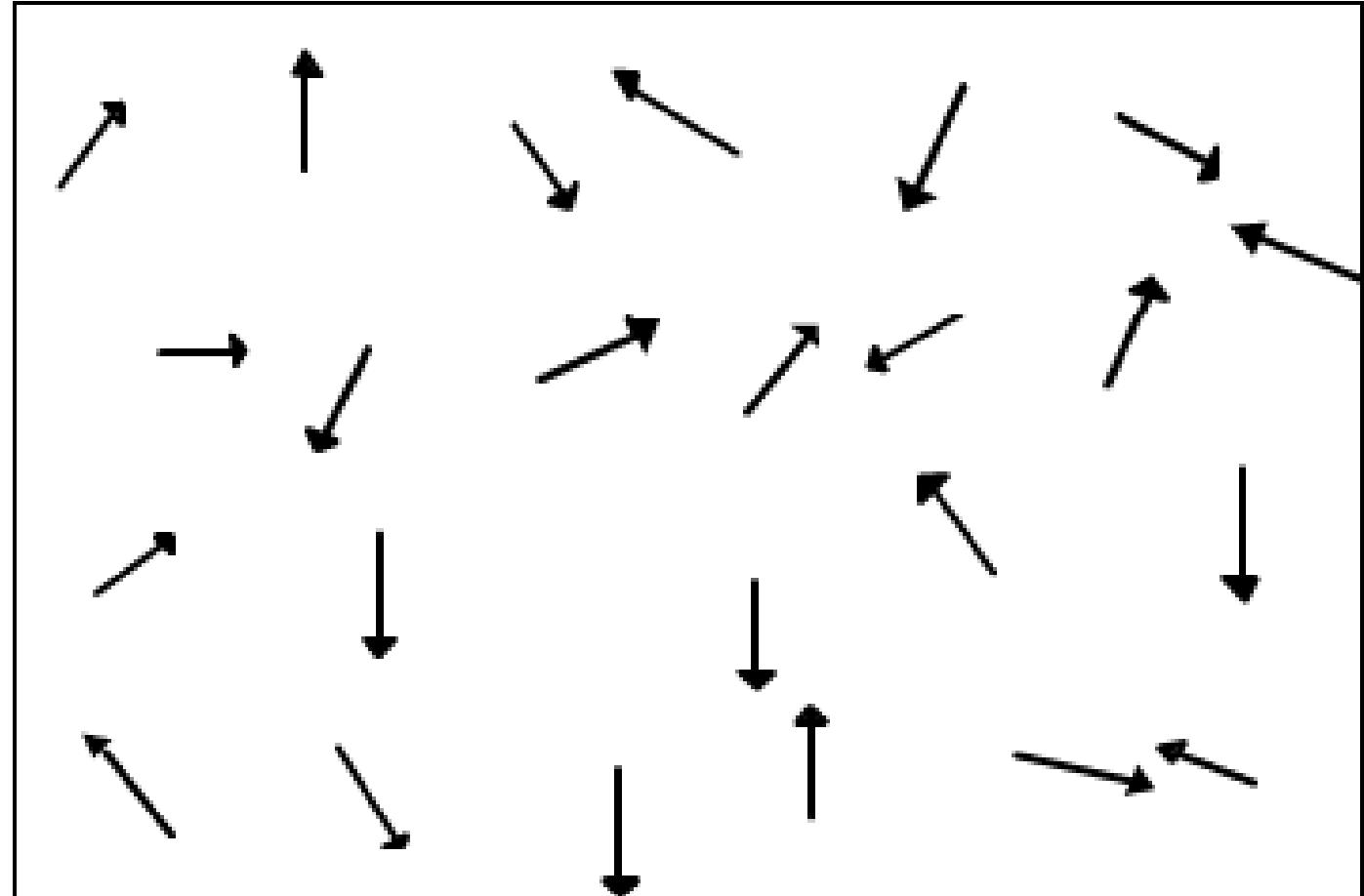
The dipoles would align themselves along the field lines of the external field for minimum energy

The dipoles are oriented into the field and a large polarization takes place

This results in a large value of dielectric constant

# Orientation Polarization

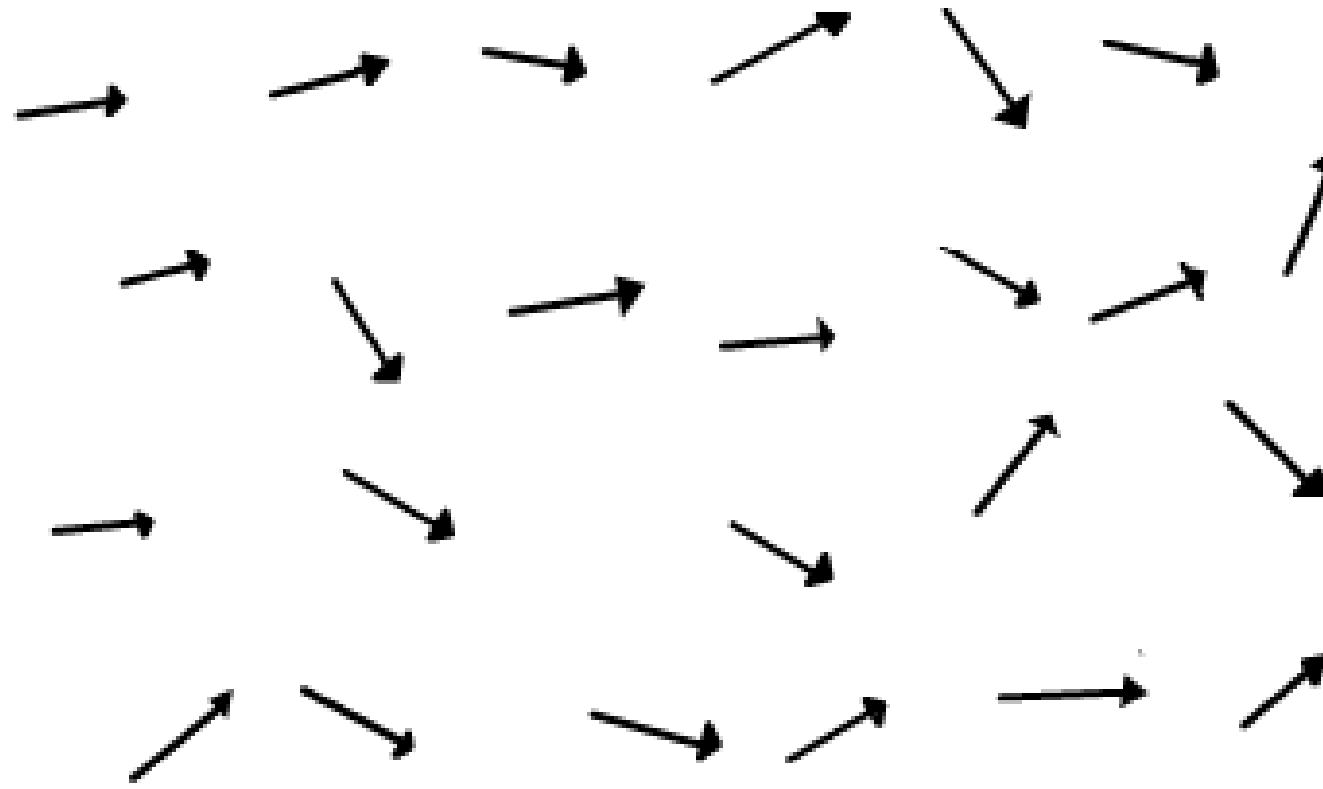
Natural dipole moments in water molecules



E

# Orientation Polarization

Natural dipole moments in water molecules



E



# Orientation Polarization

The orientation into the field direction is counteracted by random **collisions with other dipoles**

When two molecules collide together, their new orientation is random and independent of the previous orientation before collision

This process is energized by the thermal energy " $K_{th}$ " contained in the water

The thermal energy tries to randomize the orientation of the dipole moments

# Orientation Polarization

The average induced dipole moment  $\mu_{op}$  can be calculated in general as follows

$$\mu_{op} = \frac{\mu_p^2}{3K_{th}} E$$

With  $\mu_p$  is the permanent dipole moment